ATMOSPHERIC CORRECTIONS OF LAND IMAGERY USING THE EXTENDED RADIOSITY METHOD

by

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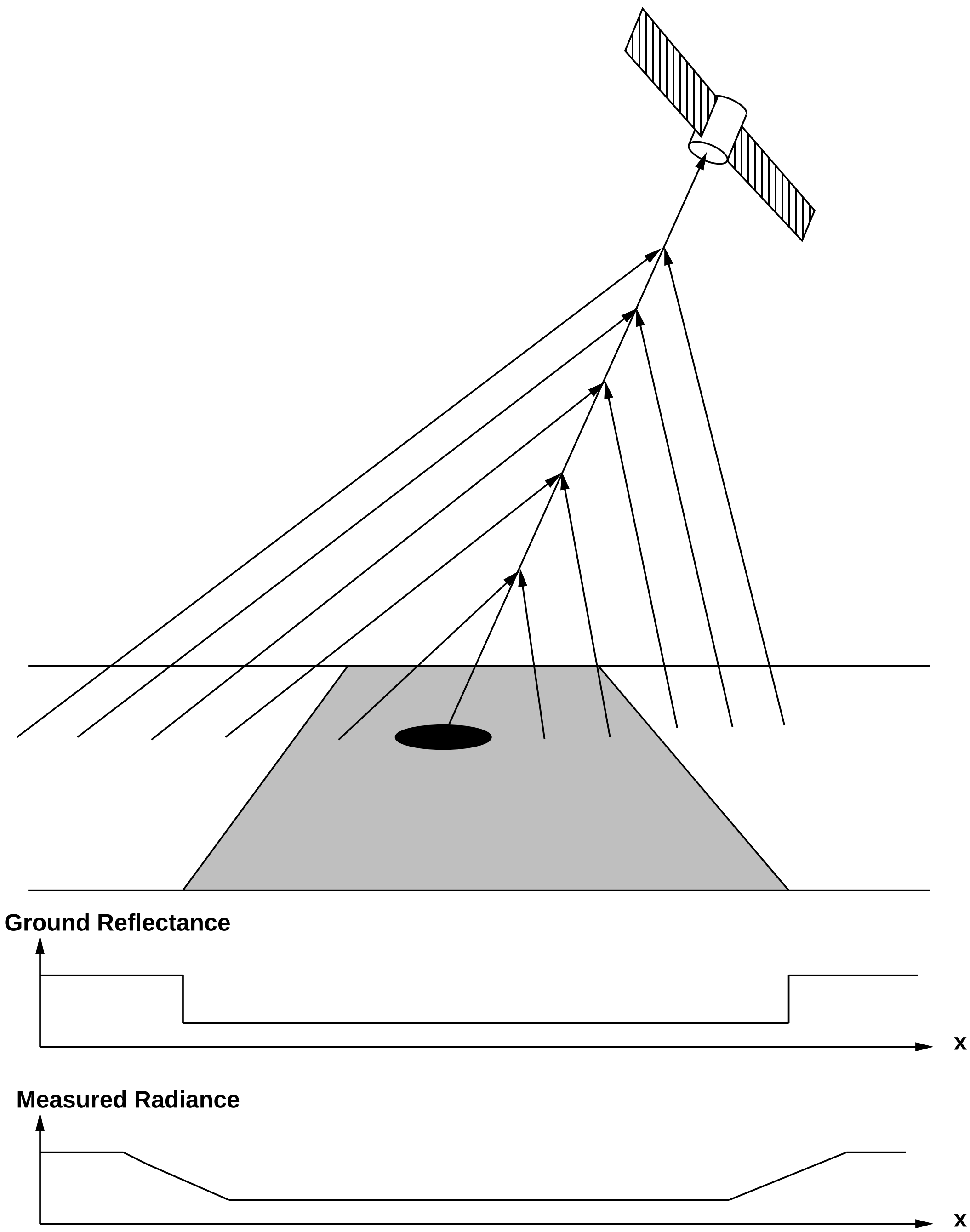
Content



Adjacency-blurring-effect over a discontinuity of reflectances

Adjacency-Blurring-Effect

Effects on sensor performance :

- Borders between bright and dark surfaces blurred
- Errors in the detection and classification of small bright targets surrounded by a dark region or dark targets on a bright background
- Reduction of contrast

How can we model the adjacency-blurring effect ?

- Point Spread Function (PSF)
- (Blurred scene) = (unblurred scene) $\otimes$ PSF

Methods to calculate PSF's :

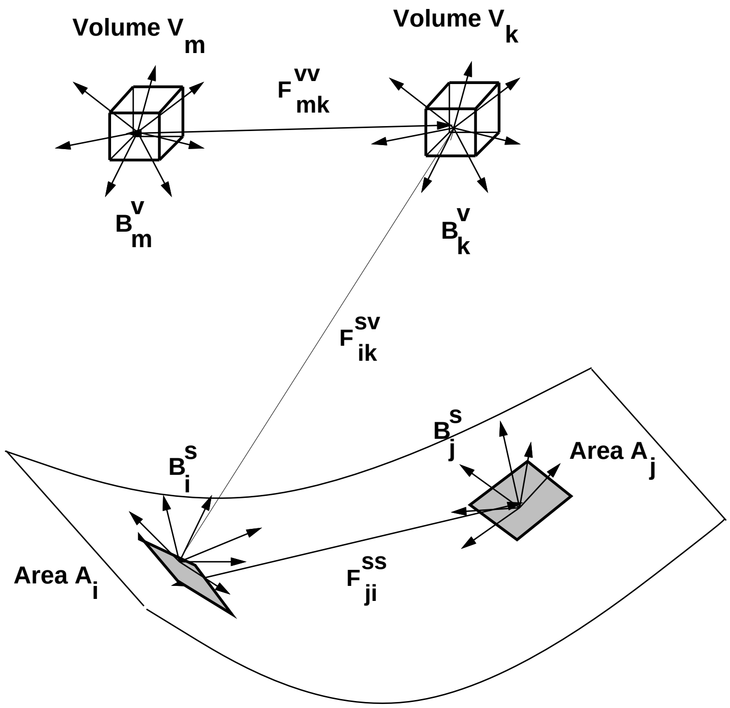
- Radiative transfer calculations
- Monte Carlo simulations

Properties of PSF's :

- Rotationally symmetric for nadir views if surface Lambertian
- Mirror symmetric for oblique views if surface Lambertian
- Asymmetric for any view direction if surface in non-Lambertian

Summary of the Extended Radiosity Method

The extended radiosity method is based on radiative transfer and considers energy exchange between volume/volume, volume/surface, surface/volume and surface/ surface elements.



Assumptions :

- Isotropic, volumetric emission and scattering by the participating medium for the volume elements
- Diffuse (Lambertian) reflection from opaque surfaces
- Arbitrary directional illumination

Extended Radiosity Equations

Surface radiosity balance equation :

$$B_i^s\ A_i \quad = \quad E_i^s\ A_i\ +\ \rho_i \left[\sum_{j=1}^{N_s} B_j^s\ F_{ji}^{ss} + \right.$$

$$\left. + \sum_{k=1}^{N_v} B_k^v\ F_{ki}^{vs} \right], \quad i\ =\ 1, \ldots, N_s,$$

Volume radiosity balance equation :

$$4\ \kappa_{t,k}\ B_k^v\ V_k \quad = \quad 4\ \kappa_{a,k}\ E_k^v\ V_k\ +\ \alpha_k \left[\sum_{j=1}^{N_s} B_j^s\ F_{jk}^{sv} + \right.$$

$$\left. + \sum_{m=1}^{N_v} B_m^v\ F_{mk}^{vv} \right], \quad k\ =\ 1, \ldots, N_v,$$

where

B_i^s is the surface radiosity in $[W\ m^{-2}]$,

E_i^s is the emission in $[W\ m^{-2}]$,

ρ_i is the reflectance $[unitless]$ of surface patch i with area A_i,

$4\ \kappa_{t,k}\ B_k^v\ V_k$ is the flux density in $[W]$ leaving a volume element k,

$\kappa_{t,k}$ is in $[m^{-1}]$ and is the sum of the absorption coefficient $\kappa_{a,k}$ and the scattering coefficient $\kappa_{s,k}$,

B_k^v in $[W\ m^{-2}]$ is the volume radiosity

$\alpha_k = \kappa_{s,k}/\kappa_{t,k}$ is the scattering albedo of the k-th volume element

F_{kj}^{ss} is the view factor from a surface k to surface j in $[m^2]$,

F_{ki}^{vs} is the view factor from volume k to surface i in $[m^2]$,

F_{jk}^{sv} is the view factor from surface j to volume k in $[m^2]$,

F_{mk}^{vv} is the view factor from volume m to volume k in $[m^2]$.

Interpretation :

Above eqs. state that the volume and surface radiosities are given by the sums of the emission and the scattered and reflected radiosities from all other surfaces and volumes.

Viewfactor :

$$\text{Viewfactor} = \frac{\text{Total energy emitted or scattered by a surface or volume arriving at another surface or volume}}{\text{Radiosity of the source surface or volume}}$$

A Method to compute the Measured Radiance over a Flat Surface

Assumption :

- Adjacency effect due to scattering of light from surface into line of sight

Steps :

1. Compute radiosity from a volume element k along line of sight due to light coming from a surface patch j : $4\kappa_{t,k}\ B_k^v\ V_k$
2. Compute radiosity leaving surface patch i : B_i^s
3. Compute measured radiance at sensor level: $I(L)$

STEP 1 :

The radiosity from a volume is given by the sum of the volume emitted radiosity and the radiosity scattered from surrounding surfaces :

$$4\ \kappa_{t,k}\ B_k^v\ V_k \quad = \quad 4\ \kappa_{a,k}\ E_k^v\ V_k\ +\ \alpha_k \sum_{j=1}^{N_s}\ B_j^s\ F_{jk}^{sv}\ ,$$
$$k\ =\ 1, \ldots, N_v.$$

STEP 2 :

The radiosity leaving the ground surface is then given by :

$$B_i^s\ A_i\ =\ E_0\ \rho_i\ \exp\left(-\frac{\kappa_t\ L}{\cos\theta_s}\right)\ A_i\ ,\qquad i\ =\ 1,\ldots,N_s,$$

where

$\exp(-\kappa_t\ L/\cos\theta_s)$ is the atmospheric transmittance,

θ_s is the sun zenith angle.

STEP 3:

The measured intensity at the sensor, located above the atmosphere at distance L and tilted by the angle θ_r from zenith for a homogeneous atmosphere with K layers of equal thickness, can be approximated with :

$$I(L)\ =\ \exp(-\kappa_t\ L)\ \frac{B_i^s}{\pi} + \sum_{k=1}^{K}\ \exp(-\kappa_t\ (K-k)\Delta l)\ \frac{B_k^v}{\pi}\ \kappa_t\ \Delta l,$$

where $\Delta l\ =\ L/K\ \cos\theta_r$

Substituting result from step 1+2 :

$$\begin{aligned} I(L)\ =\ \frac{1}{\pi}\ \Big[E_0\ \rho_i\ \exp\left(-\frac{\kappa_t\ L}{\cos\theta_s}\right)\ \exp\left(-\frac{\kappa_t\ L}{\cos\theta_r}\right)\ +\ \sum_{k=1}^{K}\ \Big\{\frac{\kappa_a}{\kappa_t}\ E_k^v \\ +\ \frac{\alpha_k}{4\ \kappa_t\ V_k}\sum_{j=1}^{N_s}\ E_0\ \rho_j\ \exp\left(-\frac{\kappa_t\ L}{\cos\theta_s}\right)\ F_{jk}^{sv}\Big\} \\ \kappa_t\ \exp(-\kappa_t\ (K-k)\ \Delta l)\ \Delta l\Big], \end{aligned}$$

where the view factor F_{jk}^{sv} between surface patch S_j and volume element V_k is given by:

$$F_{jk}^{sv} = \frac{\kappa_t \; V_k \; \tau(r_{kj}) \; \cos\theta \; f(\theta_{p,k}) \; A_j}{\pi \; r_{kj}^2}$$

where

$f(\theta_{p,k})$ is the scattering phase function,

$\theta_{p,k}$ is the phase angle,

$\tau(r_{kj})$ is the transmission factor $\tau(r_{kj}) = \exp(-r_{kj} \; \kappa_t)$ and

r_{kj} is the distance between surface element j and volume element k along the line-of-sight ($k = 1$ is bottom and $k = K$ is top).

<u>Observation :</u>

Equation for $I(L)$ can be interpreted as a sum of attenuated radiance from the ground plus the convolution of ground reflectance with a point spread function.

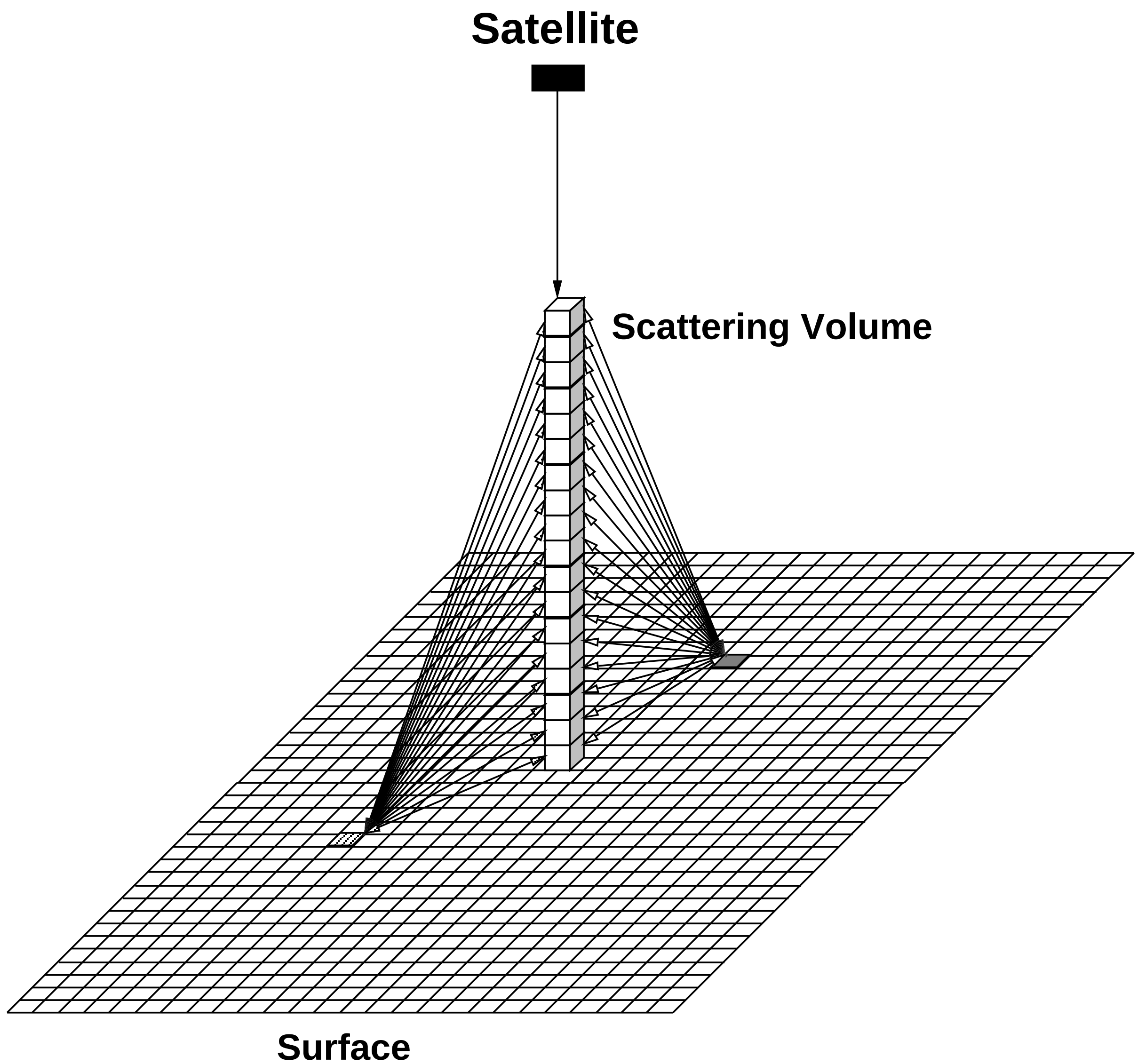
Measured Radiance at the Sensor for Lambertian Surfaces

$$
\begin{aligned}
I_{measured}(x, y, \ldots) \quad = \quad & \frac{E_0}{\pi}\tau_s\big[\tau_r \rho(x_0, y_0) \\
& + \rho(x, y) \otimes PSF(x, y, \ldots)\big] \\
& + I_{path}
\end{aligned}
$$

where

- E_0 is the direct energy incident from the sun in $[W\ m^{-2}]$,
- $\tau_s = \exp(-\kappa_t L_z / \cos\theta_s)$,
- $\tau_r = \exp(-\kappa_t L_z / \cos\theta_r)$,
- $\rho(x, y)$ is the reflectance at point (x, y),
- $\otimes$ denotes the convolution and
- I_{path} is the path radiance or radiance due to scattering in the atmosphere.

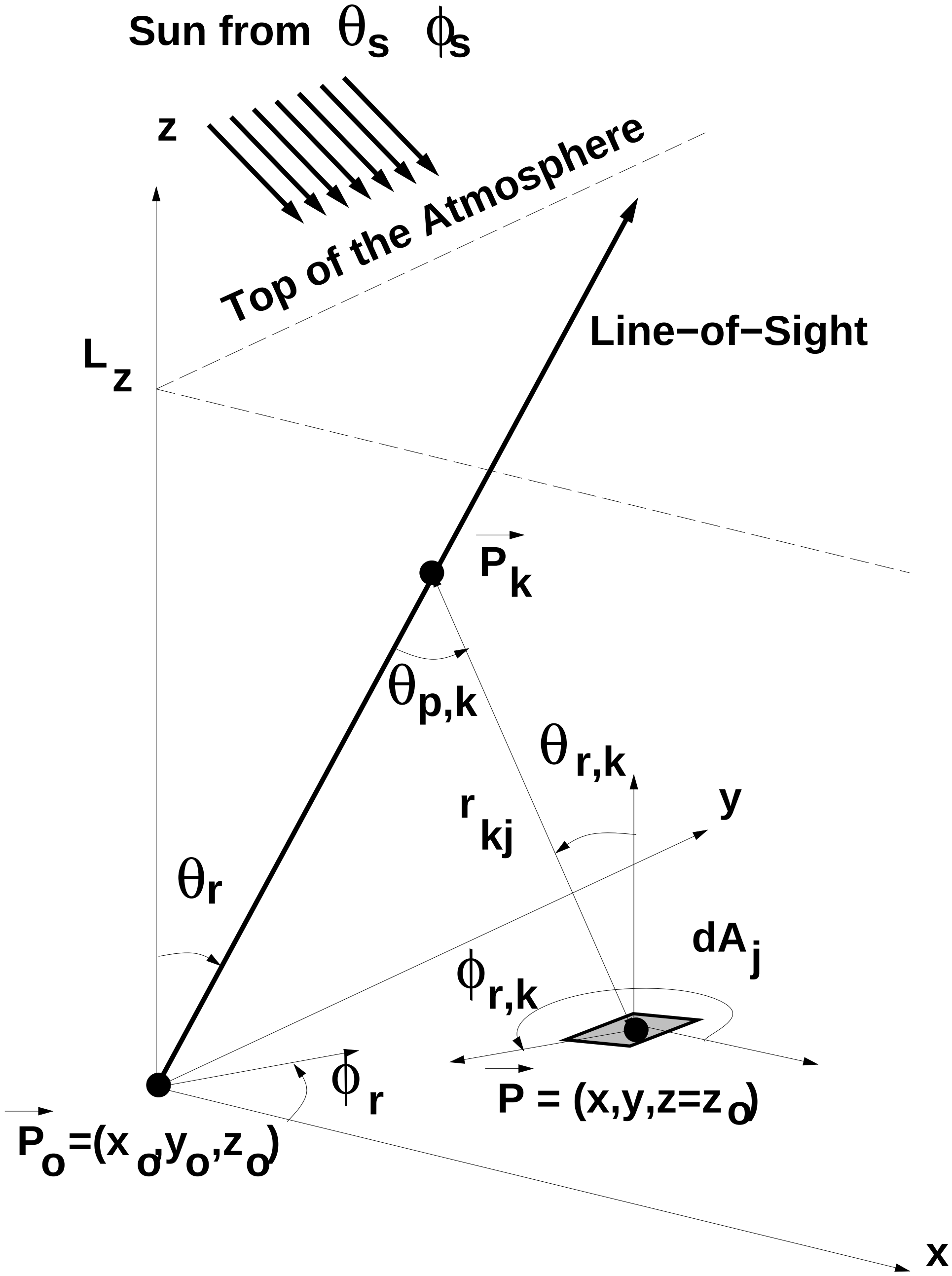
Atmospheric Point Spread Function



Definition: The point spread function :

$$PSF(x, y, z; x_0, y_0, z_0; \theta_s, \phi_s; \theta_r, \phi_r)$$

can be defined as the scattering contribution of a surface element $dA = dx\ dy$ illuminated from direction (θ_s, ϕ_s) located at $(x, y, z = z_0)$ into the line-of-sight direction of the observer (θ_r, ϕ_r) looking at point (x_0, y_0, z_0).



Point Spread Function for Lambertian Surfaces :

$$PSF(x,y,\ldots) \quad = \quad \frac{\kappa_s\ \Delta l}{4\ \pi} \sum_{k=1}^{K} \frac{\tau(r_k)\ \cos\theta_k\ f(\theta_{p,k})\ dx\ dy}{\pi\ r_k^2} \cdot \exp(-\kappa_t\ (K-k)\ \Delta l),$$

where we set the surface radiosity:

$E_0\ \rho(x,y,z=z_0)\ \exp(-\kappa_t L_z/\cos\theta_s) = 1$

for normalization purposes and where:

$\tau(r_k)\ =\ \exp(-\kappa_t\ r_k),$

$r_k\ =\ |\vec{P_k} - \vec{P}|,$

$\cos\theta_k\ =\ kb_z/r_k$ and

$$\theta_{p,k}\ =\ \cos^{-1}\Big[\frac{(\vec{P_0}-\vec{P_k})\cdot(\vec{P}-\vec{P_k})}{|\vec{P_0}-\vec{P_k}|\ r_k}\Big]$$

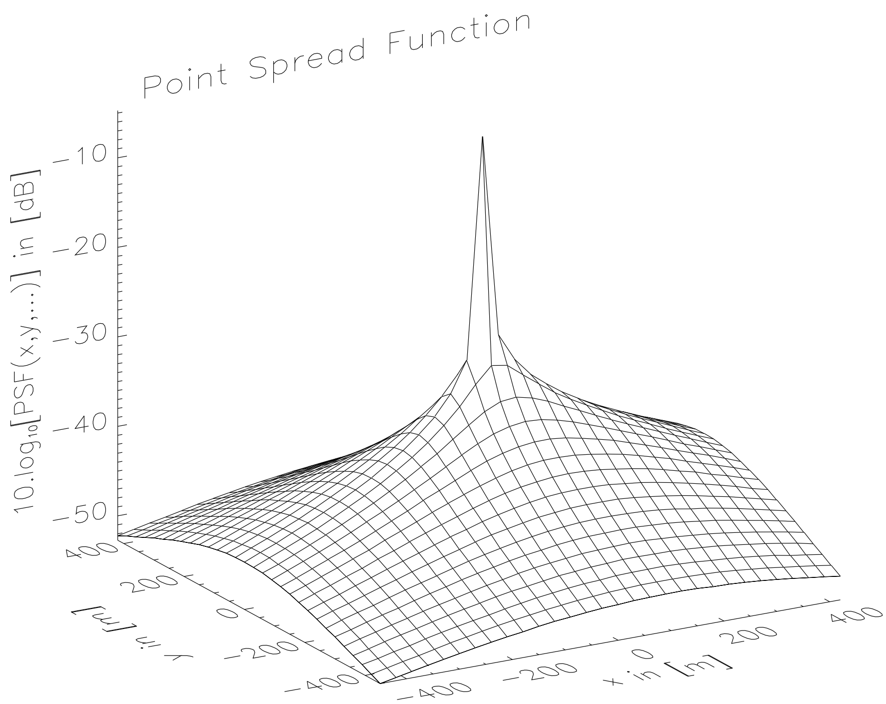
.

Measured scene radiance $I_{measured}(x,y)$ in $[W\ m^{-2}]$ at the detector location above the atmosphere is given by the sum of the attenuated direct scene radiance and the convolution of the point spread function with the weighted scene reflectance map and an additional path radiance I_{path}:

$$I_{measured}(x,y) \quad = \quad \frac{E_0}{\pi}\ \exp\Big(-\frac{\kappa_t\ L_z}{\cos\theta_s}\Big)\ \Big[\rho(x_0,y_0)\exp\Big(\frac{-\kappa_t\ L_z}{\cos\theta_r}\Big) + \rho(x,y)\otimes PSF(x,y,\ldots)\Big]\ +\ I_{path}.$$

Example :

The point spread function for $\kappa_a = 0.05/L_z$, $\kappa_t = 0.3/L_z$ and view angle $\theta_r = 45^0$, $\phi_r = 0^0$:



Notes :

- The size of the scattering volume was $L_x = 900\,m$, $L_y = 900\,m$, $L_z = 900\ m$ with a volume subdivision of $N_x = 30$, $N_y = 30$, $N_z = 30$ to simulate the Landsat TM sensor spatial resolution of 30 m.

- The PSF is shown in a logarithmic surface plot in dB scale to emphasize the shoulders.

- The scattering phase function was chosen to approximate a "hazy" atmosphere using the Henyey-Greenstein phase function with the asymmetry factor $g = 0.75$ (Liou (1980)). The Henyey-Greenstein phase function is given by :

$$f(\theta_p) = \frac{1 - g^2}{(1 + g^2 - 2g\cos\theta_p)^{3/2}}.$$

Removing the Adjacency Blurring Effect

1. Classic inverse filter method (Kaufman (1984) :

$$I_{corrected}(x,y) \;=\; F^{-1}\left[\frac{F[I_{measured}(x,y)]}{F[PSF(x,y,\ldots)]}\right],$$

where :

$$I_{measured}(x,y) = F^{-1}[F[I_e(x,y)]M(\omega_x,\omega_y)] + I_\beta + I_0.$$

$I_e(x,y)$ is the radiance without atmospheric effects,

I_β a correction term,

I_0 the upward radiance for a surface with zero reflectance,

$F[\cdot]$ denotes the Fourier transform,

$F^{-1}[\cdot]$ denotes the inverse Fourier transform,

ω is the spatial frequency in $[cycles/m]$ and

$M(\omega_x,\omega_y)$ is the modulation transfer function (MTF).

2. Deconvolution method (Pratt (1978)) :

The kernel for the deconvolution or inverse point spread function is given by:

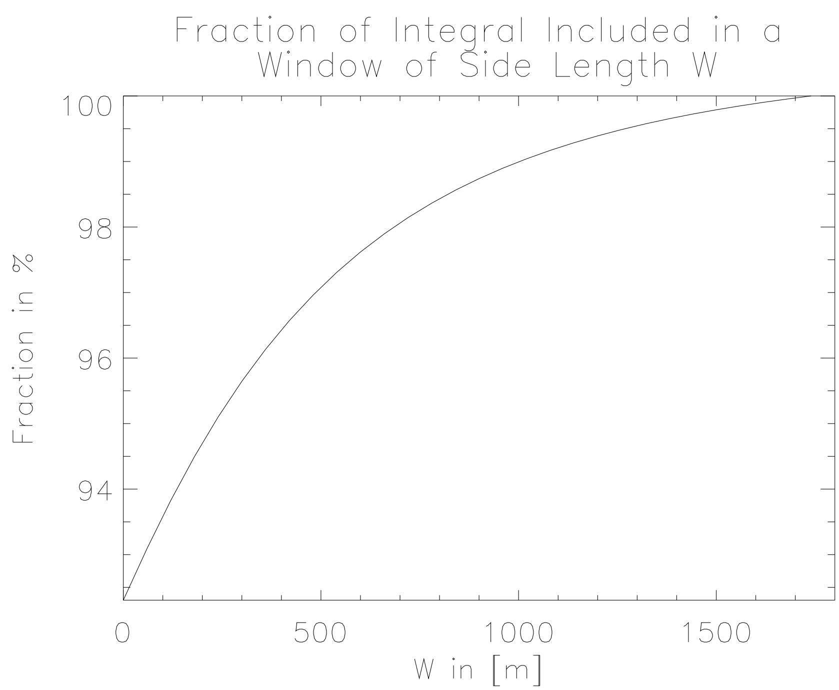
$$IPSF(x, y) = \frac{1}{N_p^4}\, F^{-1}\left[\frac{1}{F[\rho(x_0, y_0)\exp(-\frac{\kappa_t L_z}{\cos\theta_r}) + PSF(x, y)]}\right],$$

where N_p^{-4} is a factor which depends on the implementation of the FFT and N_p is the width of the PSF in pixels.

The FFT used is defined as :

$$F(\omega_x, \omega_y) \;=\; \frac{1}{N_p^2} \sum_{x=0}^{N_p-1} \sum_{y=0}^{N_p-1} \; f(x, y)\;\; \exp\Big(-\frac{j2\pi}{N_p}(x\omega_x + y\omega_y)\Big),$$

where $j = \sqrt{-1}$.



Note : Without adjacency blurring correction the measured radiance would be smaller (92 %) over a uniform surface because of neglecting the scattering contributions from adjacent surfaces.

Atmospheric Correction using Deconvolution

Observation :

The number of necessary multiplications for a small inverse filter with a window size similar to the PSF, we found it more practical to compute the adjacency corrected reflectance image by convolving the measured radiance image with the inverse PSF, $IPSF(x, y, \ldots)$ which incorporates the term :

$\rho(x_0, y_0)\ \exp(-\kappa_t\ L_z/\cos\theta_r)$

in the computation of IPSF :

$$\rho_{corrected}(x, y) \;=\; (I_{measured}(x, y) - I_{path}) \otimes IPSF(x, y, \ldots)\ .$$

Example :

For an image of size $N = N_x = N_y = 512 \times 512$ and an inverse PSF of $N_p = 12 \times 12$ pixels it takes :

$$M_{deconvolution} \;=\; N_x \;\times\; N_y \;\times\; (N_p)^2 = 37.7 \cdot 10^6$$

multiplications for the deconvolution method versus :

$$M_{FFT} \;=\; 3\ (N_x\ \log_2 N_x)(N_y\ \log_2 N_y) = 63.7 \cdot 10^6$$

multiplications for the FFT method. For larger images the savings are even greater:

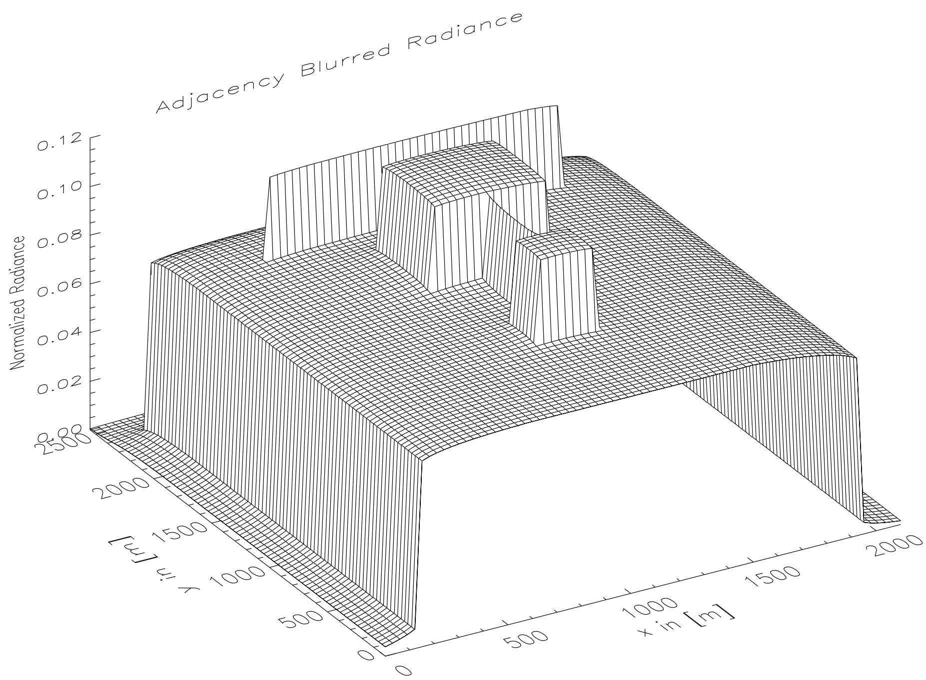
- For $N_x = N_y = 512$ image we get $N_p \leq 15$
- For $N_x = N_y = 1024$ image we get $N_p \leq 17$

Observations :

- The necessary filter size increases with increasing optical depth and scattering atmosphere height.
- Sensors with coarser resolution smaller filter have smaller filter sizes.

Example Scene

To illustrate the deconvolution method with an example we created an artificial scene containing various squares and rectangles at various sizes with constant reflectance. Atmospheric parameters : $\kappa_t = 0.8$, $\kappa_a = 0.032$



Observations :

- The radiance decreases due to the adjacency effect for small bright targets as seen for the small squares, and the thin line in the upper part of the image.
- Sharp discontinuities are smoothed out producing a sigmaoid shaped transition.
- The radiance of the small darker squares surrounded by the bright area is increased.
- Due to the asymmetry of the point spread function edges have an orientation dependent transition.

Landsat image over Boulder, Colorado : View angle $\theta = 80^0$, $\phi = 0^0$

1. Adjacency filtered image
2. Adjacency de-blurred image
3. Difference between 1) and 2)

Conclusions

- We have presented a method to compute the point spread function for off-nadir pointing sensors using selected parts of the radiosity equation.

- We showed that the point spread function is in general asymmetric.

- The radiosity based method is able to include scattering phase functions and atmospheric parameters for a stratified atmosphere.

- A Fourier transform based method is able to recover the radiance.